Adaptive multi-sensor biomimetics for unsupervised submarine hunt (AMBUSH): Early results

Stéphane Blouin

Defence R&D Canada - Atlantic Research Centre, 9 Grove Street, Dartmouth (NS), Canada

ABSTRACT

Underwater surveillance is inherently difficult because acoustic wave propagation and transmission are limited and unpredictable when targets and sensors move around in the communication-opaque undersea environment. Today's Navy underwater sensors enable the collection of a massive amount of data, often analyzed offline. The Navy of tomorrow will dominate by making sense of that data in real-time. DRDC's AMBUSH project proposes a new undersea-surveillance network paradigm that will enable such a real-time operation. Nature abounds with examples of collaborative tasks taking place despite limited communication and computational capabilities. This publication describes a year's worth of research efforts finding inspiration in Nature's collaborative tasks such as wolves hunting in packs. This project proposes the utilization of a heterogeneous network combining both static and mobile network nodes. The military objective is to enable an unsupervised surveillance capability while maximizing target localization performance and endurance. The scientific objective is to develop the necessary technology to acoustically and passively localize a noise-source of interest in shallow waters. The project fulfills these objectives via distributed computing and adaptation to changing undersea conditions. Specific research interests discussed here relate to approaches for performing: (a) network self-discovery, (b) network connectivity self-assessment, (c) opportunistic network routing, (d) distributed data-aggregation, and (e) simulation of underwater acoustic propagation. We present early results then followed by a discussion about future work.

Keywords: Underwater, surveillance, sensor network, distributed computing, adaptation.

1. INTRODUCTION

Real-time underwater sensor networks have the potential to revolutionize oceanographic data collection, pollution monitoring, offshore exploration, assisted navigation, marine habitat protection, tracking of marine mammals, and surveillance. This promise explains the recent proliferation of academic research activities associated with underwater sensor networks. Despite its popularity, this active field of research has not yet exhausted all practical challenges, especially in areas such as distributed computing and adaptive automation.

Acoustic waves propagate much further underwater than electromagnetic or optical waves,[1] thus underwater network nodes usually rely on acoustic sensors. Similarly, the primary medium for wireless underwater communications between network nodes tends to be through acoustic waves. Unfortunately, underwater acoustic communications are unpredictable due to environmentally-driven frequency-dependent attenuation, time-varying multipath effects, large Doppler and delay spreads, and limited bandwidth.[2]

This document provides an overview of the work achieved in the first year of DRDC's AMBUSH research project that was awarded DRDC's Technology Investment Fund (TIF) in 2012. The main objective of this project is to maximize the performance of long-term, undersea and wireless networked sensors[3].[4]

Further author information: (Send correspondence to S.Blouin.)
S.Blouin: E-mail: stephane.blouin@drdc-rddc.gc.ca, Telephone: 1 902 426-3100 (x216)

DRDC-RDDC-2014-P59

2. BACKGROUND

2.1 Navy's current capability and tomorrow's needs

Military undersea-surveillance networks are usually wired and deployed in controlled waters. Today's use of undersea sensing technology for surveillance purposes could be qualified as requiring high-bandwidth, frequent communication, centralized data-aggregation, and significant operator and analyst overhead. These characteristics limit such networks to friendly waters and to a human-manageable analysis capacity.

Today's underwater sensors enable the collection of a massive amount of data, often analyzed offline. Tomorrow's Navy will dominate by making sense of that data near real-time.

Often, NATO coalition members are tasked to patrol or secure strategic choke points with a small number of warships away from friendly waters. These situations keep the ship crew and assets within the reach of an opposing force, thus requiring a high-level of readiness over extended periods of time. For maximal protection, warships should be able to deploy and remotely operate an undersea-surveillance network to increase their standoff distance. For optimal operational effect, such an undersea-network should also be able to operate in an unsupervised mode while exploiting the changing undersea environment to its advantage.

Despite their increasing presence, unmanned systems can not yet fully resolve the gap between today's Navy capability and tomorrow's needs due to their rudimentary autonomy and very limited collaboration among themselves and with other platforms.[5]

2.2 Nature's inspiration filling the gap

Recent demonstrations of the network-centric warfare revealed the advantages of networked collaborations.[6,7] A logical extension would be to integrate similar collaboration ideas in undersea-surveillance networks. Such a concept could potentially enhance operations, tactics, and strategies.

Luckily, Nature can still teach us some important lessons about collective behaviours. First, collaboration occurs among insects (Figure 1(a)) thus indicating that the required level of intelligence to collaborate may not be as sophisticated as initially anticipated. Secondly, from simple and individualistic rules can emerge collective behaviours, like the flying formation of migrating birds shown in Figure 1(b).[8] Such emergent behaviours often are robust. Indeed, if a hunter takes down the leading bird, another one automatically takes its place. Lastly, collective hunting strategy is much more efficient than hunting in solo. It was recently demonstrated in simulation that the wolf-pack collective hunting behaviour can be re-created using simple rules that do not require any communication between predators.[9] Altogether, these findings open new possibilities in that robust collaboration may arise from simple rules despite scarce communication and limited computational capability.

(a) (b) (c)

Figure 1. Nature's lessons: (a) Collaborative insects, (b) Emergent collective behaviour, and (c) Minimally communicating hunters.

Mainstream research has derived partial answers for enforcing collaboration on terrestrial or aerial networks but, to this day, there has been no implementation of a collaborative and adaptive wireless undersea-surveillance sensor-network.

3. PROJECT DESCRIPTION

Inspired by Nature, this research project intends to fill the technological gap enabling tomorrow's Navy to perform their missions more efficiently.

3.1 Underwater network setup

The envisioned undersea network will be deployed in shallow waters and continental shelf locations with a partial or complete ice cover. The proposed network will be made of a large collection of intelligent, static, and wireless sensory nodes augmented by fewer mobile sensory nodes, or autonomous underwater vehicles (AUV). Static nodes will provide the permanent sensor barrier whereas mobile nodes will enable the exploration of new areas, a more complete analysis of the water column, and the creation of novel network-relay communication paths. Mobile nodes may also act as gateway links in presence of a complete ice cover if submerged docking stations are available for recharging batteries and passing data to the outside world. Even though unsupervised, the proposed network maintains a human-in-the-loop in that it will require operator interventions, but only for tough decisions.

3.2 Project objectives

The main objective of the AMBUSH project is to maximize the performance of long-term, undersea and wireless networked sensors made of mobile and fixed nodes through *distributed localization*, *collaboration*, and *adaptation*.

Distributed target-localization is the main task of the networks studied throughout this project. By "distributed", it is meant that undersea sensors will behave like an intelligent collective entity to localize a target of interest. As opposed to traditional systems where data is centralized to a single platform, like one-way sonobuoy data channeled to a single radio-receiver, this project favors two-way data dissemination across the entire network. Distributed paradigms are usually more robust to individual node failure than centralized ones.

Adaptation is a key feature to enable a satisfactory unsupervised behaviour. Adaptation will help network nodes tune their collective performance in response to the dynamically changing undersea environment, which strongly influences underwater acoustic detection and communication.

Similar to the wolf-pack hunting strategy, *collaboration* among network nodes is believed to augment the success and the robustness of the target-localization mission. Underwater communications are a necessary condition for collaboration and distributed localization to take place.

A particular network-performance criteria that this project focuses on is the robustness to dynamically changing conditions. For instance, it is assumed that the network size and topology will not be known by sensor nodes. This assumption accounts for the fact that nodes could be added at later times and that some nodes may stop operating or be dislodged by fishing nets or other events. Consequently, the proposed network must be self-aware in that each network node needs to maintain its own up-to-date representation of the network composition.

3.2.1 Scientific objectives

This project requires the identification and enforcement of conditions enabling a stable, adaptive, and distributed target-localization task. The main research themes covered by the project are:

- Network discovery,
- Network connectivity monitoring,
- Distributed target-localization,
- Impact of intermittent communications on localization,
- Adaptation due to changing environmental conditions, and
- Fast and opportunistic message routing.

Taken separately, collaboration, distributed localization, or adaptation is novel for undersea networks; together, these features represent a revolutionary way of performing undersea surveillance.

The novelty of this research project is also its Achilles' heel. Indeed, the main roadblock for exploiting the collaboration potential described above is a lack of theoretical and experimental results on networked-sensor data aggregation that are readily applicable to the underwater environment. Most wireless network results apply to terrestrial scenarios assuming a known network structure, bidirectional communications,[10] instantaneous multi-hop,[11] or peer-to-peer[12] links, whereas

undersea communications are often unidirectional and of the broadcast type with strong variability. Partial solutions to sub-problems may be found in the literature, but no particular contribution addresses the problem as a whole in the context of an underwater environment. However, the fact that Nature so perfectly enforces collaboration in restrained-communication conditions implies realistic and reachable scientific objectives.

3.3 Project management

This project adopts a sequential approach comprised of theoretical studies, simulations, and experiments. Theoretical studies incorporate undersea-communication features while addressing the above scientific goals. Most of these studies are pursued concurrently and independently for maximizing the overall project success. The project execution relies on a combination of in-house, collaborative, and contracted work engaging DRDC, external contractors, and academic partners. To support the project, four research contracts were awarded on the following topics:

- Network connectivity: Derive techniques an identify conditions for assessing global-network connectivity based on local information exchanges only. Local exchanges mimic underwater communication properties.
- Data aggregation: Aggregate bearing-only data in a distributed manner through underwater communications. Real underwater acoustic data is used to develop and test various target-localization algorithms.
- Robust networking: Derive mechanisms to perform opportunistic routing among networks made of both mobile and static nodes.
- Acoustic propagation: Develop a range-dependent simulator for shallow water environments that includes the effect of water currents and ice covers.

Proposed solutions derived through these research contracts will be validated experimentally with purpose-built experimental equipment described next.

4. PLANNED EXPERIMENTS

A series of experiments to test underwater networking concepts already started to take place in the Bedford Basin whose bathymetry is shown in Figure 2. The Bedford Basin is adjacent to the Halifax Regional Municipality (HRM) located on Canada's Atlantic coast. Its main peculiarities are its relatively great depth and the mix of fresh and ocean waters in it as well as strong currents at its mouth, The Narrows.

The planned experiments involve relatively simple network nodes shown in Figure 3(a) whose main components are a radio, an antenna, a Global Positioning System (GPS), an acoustic modem, and a battery pack. The configuration of the internal electronics is illustrated in Figure 3(b). This basic, lightweight, and affordable node design enables a relatively simple assembly and manual deployment. The design simplicity originates from the decision of *not* including any sensor or computational capability in the node. Instead, commands and queries will happen through radio communications. Even though simple in design, such nodes enable the testing of various algorithmic real-time concepts. Even though the computation capability is centralized on DRDC's site, the computation runs each node computational logic separately. The computational scheme queries each node to determine which one received the underwater acoustic message before determining what is the next message to send.

A series of experiments relating the impact of underwater acoustic modem parameters (bit rate, power level, message length and distance) on the occurrence of successful acoustic communications just ended in August 2014 and its results will be soon published.

5. SUMMARY OF EARLY RESULTS

Results presented here are grouped under two main topics: *distributed computing* and *underwater acoustics*. Those results were selected based on their potential impact on the design and/or operation of the proposed network nodes.

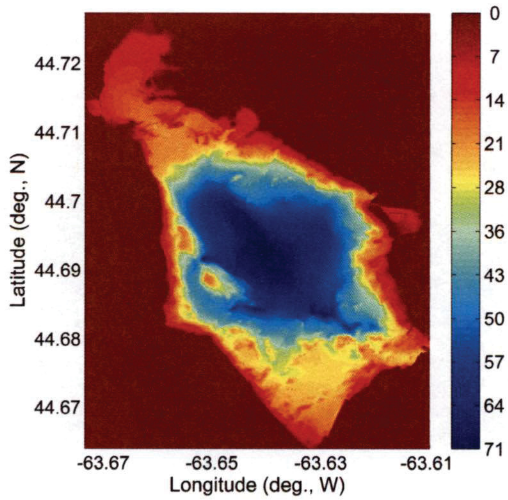
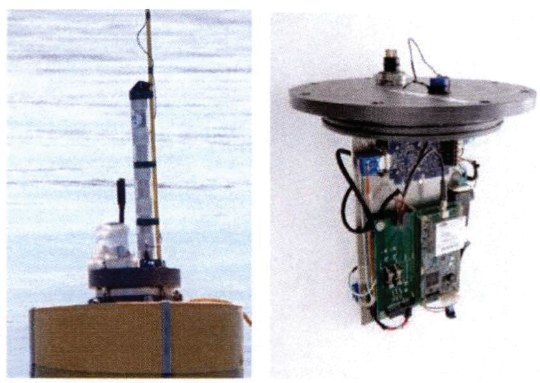


Figure 2. Bedford basin bathymetry (Canadian Hydrographic Service)



(a) (b)

Figure 3. Network node: (a) surface expression, (b) electronics.

5.1 Distributed computing

Distributed computing is a necessary technology enabling the proposed network nodes to collectively determine the network size and composition, to assess the global network connectivity, to route a message from a source node to a sink node, and to localize a target. Consequently, results pertaining to distributed computing are further broken down in *network discovery*, *network connectivity*, *routing*, and *target localization*. Moreover, we present results about *network simulation* as testing such algorithms in a simulated environment is more affordable and simpler then performing sea trials.

- Network discovery[13]
  - A relatively simple network discovery scheme, only requiring two user inputs and not requiring *a priori* network knowledge, has been derived and tested in simulation.
  - For discovering network size and composition, broadcasting the entire network structure estimates becomes more important at low probabilities of received communications, which is the condition likely to prevail under water.
  - Network structure estimates may lag the actual network structure.

- Network connectivity[4, 14]
  - A learning algorithm based on vertex connectivity is developed so that each sensor updates its belief on the probabilities of expected communications using the broadcast messages they receive.
  - There is a trade-off for estimating the network connectivity based on local data exchanges only in that the estimation accuracy of the communication probabilities degrades when the convergence rate is increased.
  - A novel measure to evaluate the connectivity of the network is proposed. The weighted vertex connectivity extends the vertex connectivity metric by captu-ring the probabilistic nature of underwater communications.
- Network routing[4, 15]
  - A location-free routing scheme was developed based on the presence of depth sensors.
  - A refraction-based routing approach was derived to exploit direct communication paths. Necessary and sufficient conditions were derived for the existence of a point-to-point link and a generalization to routes was developed.
- Target localization[4, 16, 17]
  - Experimental sea-trial data was provided and used to compare various distributed target-localization algorithms.
  - Given the non-linearities in both target dynamics and sensor measurements, most efforts have focused on distributed particle filtering and distributed ensemble Kalman filtering. This is the first time that decentralized particle filters have been carefully compared using experimental data.
  - The proposed Ensemble Kalman Filter schemes clearly outperform state-of-the-art non-linear distributed tracking alternatives despite a severe reduction in the number of scalars it is allowed to transmit.
  - Unreliable underwater communications impact distributed localization schemes. The impact of message reception probability on localization performance is non-trivial in that even though the trend is clear, the magnitude of the impact does not exhibit a simple linear relationship. Increased communications reduce both the mean time-averaged square error and the error variance.
  - There is a trade-off arising when using distributed particle filtering in that a larger number of particles improves the tracking accuracy at the cost of an increased communication cost.
  - When using bearings only, co-linear measurements make the localization problem more challenging. This highlights how (a) sensor placement matters and (b) the potential use of mobile nodes to gain distinct aspects with respect to the target.
  - Estimating the underwater acoustic channel can help improve the accuracy of the target localization and help detect anomalies.
- Network simulation[4, 18]
  - A simulator of underwater communications was developed for sensor networks comprising mobile nodes.
  - The physical layer is simulated through Matlab and takes into account attenuation, noise and their effect on a phase shift keying signal.
  - The simulator also integrates the link and network layers through OMNeT++.

5.2 Underwater acoustics

Accurate simulations of underwater acoustics are also very important as they can be used to design networks and test various algorithms. In particular, the present project aims at developing a hardware-in-the-loop underwater acoustic simulator so that experimental equipment (acoustic modems, projectors, hydrophones, etc.) can be evaluated prior to performing a sea trial. The following results relate to the development and testing of this underwater acoustic propagation simulator for shallow water environments.

- An underwater acoustic propagation simulator was put together using the BELLHOP[19] ray tracer, Virtex and Matlab.
- The BELLHOP ray tracer was modified to study the impact of water currents on acoustic propagation.
- Even though water currents do not impact Doppler spread, simulations showed how a poor sampling of the water current profile can severely affect the resulting impulse response.
- Water currents also happen to destroy reciprocity, i.e., propagation losses from A-to-B does not equate those from B-to-A.
- Simulations also showed that the spread of time-of-arrivals is sensitive to the increase in partial ice cover.
- An increase in wind tends to make the acoustic channel more sparse, an effect that seems to diminish when in presence of an ice cover.

6. CONCLUSION & FUTURE WORK

This publication summarizes DRDC's AMBUSH efforts undertaken in the last year. This research finds inspiration in Nature's collaborative tasks to advance undersea-surveillance through the use of intelligent sensor networks made of both static and mobile nodes. Such networks are meant to be deployed in shallow waters and continental shelf locations with strong currents and a partial or complete ice cover. The research focuses on distributing intelligence and computation. Early theoretical and simulation results already provide bounds and limits about what may be practically feasible. Specifically designed network nodes were built to perform experiments. Experiments in Bedford Basin already took place and more will follow. In the course of the next year, testing and validation of various algorithmic solutions in an underwater setting will take place. In particular, specific algorithms enforcing distributed target-localization, network discovery and connectivity assessment will be tested in real underwater settings.

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